IONIZATION OF GASES BY FAST N^+ *AND* N^{2+} *IONS*

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The ionization of He, Ne, Ar, Kr, H_2 and N_2 by singly and doubly charged nitrogen ions is investigated at energies in the 0.2 to 1.8 and 0.5 to 1.8 MeV ranges, respectively. The data obtained in the present investigation on the total cross sections for slow-ion and electron production are compared with the experimental data on the cross section for electron loss or capture by N^+ and N^{2+} ions obtained by the mass-spectrometric technique. The magnitudes of the pure ionization cross sections are estimated and compared with the simplified Bethe-Born approximation. It is found that even for energies exceeding 1.4 MeV an effective charge can be introduced, approximately equal to 1.64q for N^+ ions (q is the proton charge).

1. INTRODUCTION

INVESTIGATIONS of the ionization of atoms in molecules by ions of different ionization multiplicity were made for several ions of medium masses in the vicinity region $v < v_0 = q^2/\hbar$ [1-5]. Measurements of the ionization cross sections in a wide velocity range, covering the range of velocities v both larger and smaller than v_0, were made only for the light atomic particles hydrogen and helium in different charge states[5-12]. It is of undisputed interest to increase greatly the interval of the investigated velocities for ions with atomic number $z \geq 3$, for a number of reasons. First, this yields more information on the influence of the charge of the incoming ion and the charge of its nucleus on the total and partial ionization cross sections. It is also possible that from the character of this influence it is possible to attempt to delineate the velocity regions corresponding to different mechanisms of interaction of multielectron atomic particles. Second, by obtaining ionization cross sections vs. velocity plots with maxima, we acquire information needed for the interpretation of data on the ionization of atoms and molecules by ions.

Finally, one cannot exclude the possibility of comparison of theoretical calculation with the cross sections of the pure single-electron ionization in the Bethe-Born approximation, for data obtained at the maximum ion velocity attainable in the investigation.

We report here measurements of the total cross sections σ_+ and σ_- for the production of slow positive ions and free electrons, respectively, following ionization of atoms and molecules of the gases He, Ne, Ar, Kr, H_2, and N_2 by singly and doubly charged nitrogen ions. The measurements were made in the energy intervals 200–1800 and 500–1800 keV for the N^+ and N^{2+} ions, respectively.

2. EXPERIMENTAL PROCEDURE

The investigations were performed with an experimental setup used by us earlier and described in[12]. We shall discuss here only the additions to the setup, needed to obtain doubly charged nitrogen ions. For this purpose, a beam of nitrogen ions, obtained with an electrostatic accelerator, was directed to a special charge-exchange chamber installed ahead of the entrance to the magnetic mass monochromator, which separated the doubly-charged nitrogen ions from the total beam. The procedure for the measurements of the cross sections for the ionization of the gases by the N^+ and N^{2+} ions was the same as in the cited work[12]. The measurement errors in the determination of the concentration of the molecules and in the values of the measured current amounted to approximately ±10%.

3. MEASUREMENT RESULTS AND THEIR DISCUSSION

The results of our measurements of the total cross sections for the production of free electrons (σ_-) and slow positive ions (σ_+) in the ionization of the gases H_2, N_2, He, Ne, Ar, and Kr by fast singly-charged and doubly-charged ions of atomic nitrogen are shown in Figs. 1–4.

Unfortunately, there are no published data with which to compare these results directly. It is possible, however, to verify the correctness of our results indirectly. This can be done by comparing our data concerning the total ionization cross sections σ_- and σ_+

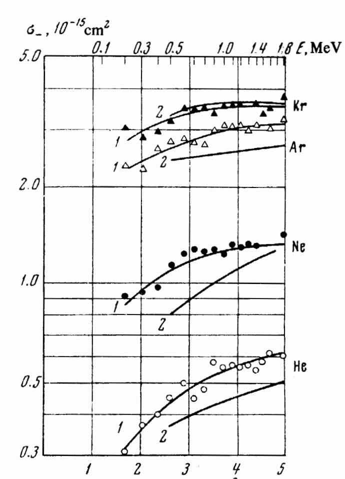


FIG. 1. Total ionization cross sections σ_- vs. nitrogen ion velocity in gases He, Ne, Ar, and Kr. The nitrogen ion charge is indicated on the curves: 1—singly-charged, 2—doubly-charged.

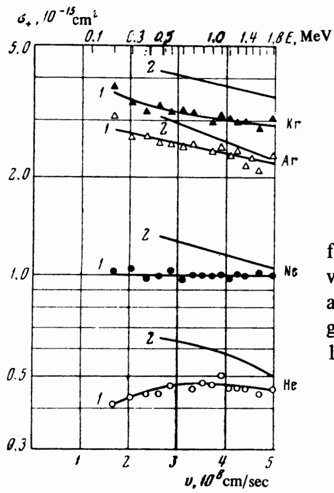


FIG. 2. Total cross sections for the production of slow ions vs. velocity in gases He, Ne, Ar, and Kr. The charge of the nitrogen ion is indicated on the curves: 1—single charge, 2—double charge.

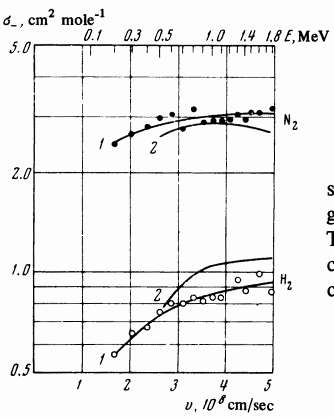


FIG. 3. Total ionization cross sections σ_- vs. velocity of nitrogen ions in the gases H_2 and N_2. The nitrogen ion charge is indicated on the curves: 1—single charge, 2—double charge.

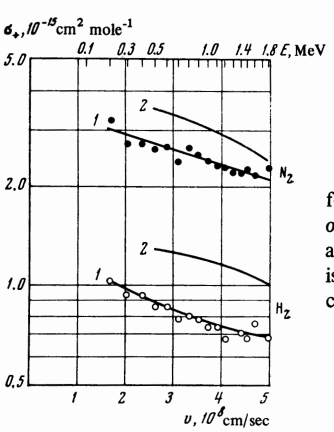


FIG. 4. Total cross sections for the production of slow ions σ_+ vs. velocity in the gases H_2 and N_2. The nitrogen ion charge is indicated on the curves: 1—single charge, 2—double charge.

with the data on the cross sections for the capture and loss of electrons by the N^+ and N^{2+} ions in the same gases, obtained by analyzing the charge composition of the primary ion beam after single collisions with the atoms and molecules of the gases. Since the positive and negative charges due to the ionization of the target molecules are equal to each other, the difference between the total negative and positive charges, recorded by the measuring electrodes, is determined only by the process of loss and capture of electrons by N^+ and N^{2+} ions, respectively. On this basis, we can write for the singly-charged nitrogen ions N^+

$$|\sigma_- - \sigma_+|_{N^+} = \sum_{m>1} (m-1)\sigma_{1m} - \sigma_{10} \quad (1)$$

and respectively for the doubly charged nitrogen ions N^{2+}

$$|\sigma_- - \sigma_+|_{N^{2+}} = \sum_{m>2} (m-2)\sigma_{2m} - (\sigma_{21} + 2\sigma_{20}). \quad (2)$$

The cross sections σ_{1m} and σ_{2m} for the loss of electrons and σ_{21}, σ_{20}, and σ_{10} for the capture of electrons by the N^+ and N^{2+} ions, which can be used for the indicated comparisons, were obtained by Nikolaev et al.[13,14], Dmitriev et al.[15,16], and Pivovar et al.[17] Comparisons made in accordance with formulas (1) and (2) for interactions of ions with He, Ne, Ar, Kr, and N_2 gas targets, for which electron capture and loss cross-section data are available, show that the indicated differences agree with one another within the limits of errors of the ionization cross section measurements. Such an agreement between measurement results obtained by entirely different methods and by different workers is to a certain degree a guarantee of the correctness of the data obtained in all cases.

In the investigated energy interval, the plots of the cross sections σ_- against the velocity are characterized by an increase of the cross section with increasing velocity and by the presence of a smeared-out maximum.

It is also seen from the figures that, with the exception of hydrogen and krypton, there is a definite dependence of the ionization cross sections σ_- on the charge of the primary particle—the nitrogen ion, namely a larger ion charge corresponds to a smaller cross section σ_-. This feature of the total ionization cross section σ_- can be naturally attributed to the fact that the smaller the charge of the incoming ion, the larger the contribution of the electron stripping reaction to the cross section σ_-. Therefore also the different dependences of σ_- on the charge in the case of hydrogen and krypton are the consequence of the relatively small contribution of the electron stripping reaction to the total ionization cross section. The cross sections σ_+ are characterized either by a monotonic decrease with increasing velocity, or by a broad maximum in the case of neon and helium.

The cross sections σ_+ also reveal a dependence on the charge of the primary particle. In this case, a larger ion charge corresponds to a noticeably larger cross section σ_+. This circumstance can be attributed to the fact that, besides the possible increase of the pure ionization cross section, an increase takes also place in the contribution of the capture of the electrons to the cross section σ_+ with increasing charge of the primary ion.

It is also seen from Figs. 1–4 that both σ_- and σ_+ increase strongly with increasing atomic number of the target atoms. This fact is apparently a general characteristic feature of the ionization processes realized by fast primary particles of different masses and charges, since analogous results were obtained also in the case of ionization of gases by protons and hydrogen atoms[6], and also by singly-and doubly charged ions and atoms of helium[9,10,18].

For the most complete interpretation possible of the data obtained in the present investigation, it is of interest to consider the cross section of pure ionization of atoms in molecules by singly-charged and doubly-charged nitrogen ions. To this end, it is necessary to introduce in the obtained data on the total ionization cross sections corrections that make it possible to exclude from the cross sections σ_+ and σ_- the contributions due to the processes of electron loss and capture by the primary fast particle. Unfortunately, the presently available data still do not make it possible to determine the exact values of these corrections, owing to the lack of information on the particle cross sections of the many-electron ionization of the target atoms in stripping and capture of electrons by the fast particle. If it is recognized, however, that removal of each succeeding electron from the target atom leads to a decrease of the corresponding cross section by approximately one order of magnitude[9,12], then we can start without a great error from the assumption that the dominant role is played by single-electron ionization. To estimate the cross sections of the pure ionization we can then use the following expressions, written out respectively for singly-charged and doubly-charged nitrogen ions:

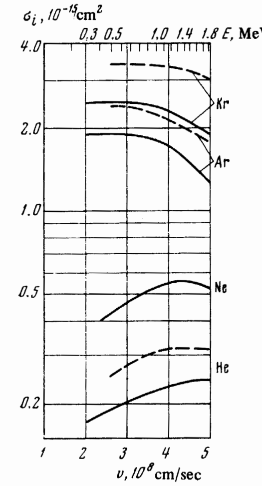
$$\sigma_i(N^+) = \sigma_+(N^+) - \Big(\sum_{m>1} \sigma_{1m} + \sigma_{10}\Big), \qquad (3)$$

$$\sigma_i(N^{2+}) = \sigma_+(N^{2+}) - \Big(\sum_{m>2} \sigma_{2m} + 2\sigma_{20} + \sigma_{21}\Big); \qquad (4)$$

σ_{1m} and σ_{2m} are the cross sections for the loss of $(m - 1)$ and $(m - 2)$ electrons by singly-charged and doubly-charged nitrogen ions respectively. It can be readily seen that in these expressions no account is taken of the partial cross sections due to the processes of multielectron ionization of atoms, accompanied by stripping and capture of electrons by the fast particle, nor is account taken of the cross section for stripping not accompanied by ionization of the target atoms.

To determine the cross sections for pure ionization σ_i we can use the values of the cross sections for the loss and capture of electrons, obtained in[13-17] and used above for a comparison of the differences of the cross sections $(\sigma_- - \sigma_+)$ with the difference of the cross sections for the loss and capture of electrons by the incoming particles. It should be noted that the cross sections of pure ionization can be estimated also in similar fashion, by starting from the total ionization cross sections σ_- and the stripping cross sections. We have made a special control verification. It turned out that the cross sections for pure ionization, estimated by these two methods, agree within the limits of experimental errors.

The cross sections of pure ionization estimated by means of formulas (3) and (4) are shown in Figs. 5 and 6. The figures show the character of the dependence of the cross sections σ_i on the velocities of the N^+, N^{2+} ions in the gases He, Ne, Ar, Kr, and N_2. In the investigated velocity interval the $\sigma_i(v)$ curve reveals a broad flat maximum, which shifts towards larger velocities with increasing first ionization potential of the target atoms. A characteristic fact is that, at least for nitrogen, argon, and krypton, the maxima of the $\sigma_i(v)$



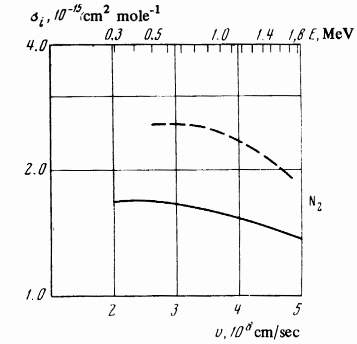


FIG. 5. Cross sections for pure ionization σ_i vs. velocity in the gases He, Ne, Ar, and Kr. Solid curves correspond to N^+, and dashed curves to N^{2+}.

FIG. 6. Cross sections for pure ionization σ_i vs. velocity in N_2. Solid curve corresponds to N^+ and the dashed curve to N^{2+}.

curves appear at velocities that are smaller than in the case of ionization of the same gases by He^+ ions or by protons.

Figures 5 and 6 give also an idea of the influence of the charge of the primary ion on the value of the cross section σ_i. With increasing charge of the nitrogen ion, the pure-ionization cross section increases systematically. It is easy to verify that the ratio of the cross sections of pure ionization by doubly-charged ions N^{2+} to the cross section of pure ionization by the singly-charged ions N^+, at equal velocities in the energy interval 500–1800 keV, either depends weakly or does not depend at all on the energy. Thus, for example, in krypton there is observed a very small increase and in nitrogen, to the contrary, a small decrease of this ratio with increasing energy. In argon and helium this ratio remains practically constant in the entire indicated energy interval. It should be noted that the ratios $\sigma_i(N^{2+})/\sigma_i(N^+)$ in the gases He, Ar, Kr, and N_2 differ little from one another, and on the average one can assume a value 1.3 for helium and argon and a value ≈ 1.4 for krypton and nitrogen. The foregoing comparison shows directly that the cross section of the pure ionization is greatly influenced by the charge of the incoming ion.

We now consider the possibility of using the Bethe-Born approximation[19] to interpret the results. A check of the ratios of the cross sections of pure ionization by nitrogen ions to the cross sections for ionization by protons of equal velocity has shown that these ratios decrease rapidly with increasing energy. However, such a decrease is observed only up to an energy on the order of 1400 keV; with further increase of the energy, the value of this ratio γ^2 remains practically constant, and amount on the average to 2.7 for the gases N_2, He, Ar, and Kr.

The quantity $\gamma^2 = \sigma_i(N^+)/\sigma_i(H^+)$ in the velocity region where it remains constant and independent of the nature of the target atoms, can be considered, using the Bethe formula[19], as a ratio of the square of the effective charge of the N^+ ions to the square of the proton charge. Therefore the effective charge of the N^+ ion is determined numerically by the value of γ, i.e., $Z_{eff} = \gamma q$, where q is the proton charge. Thus, the average effective charge of the N^+ ions at energies higher than 1400 keV is approximately equal to $Z_{eff} = \sqrt{2.7}\ q = 1.64q$. It should be noted that Z_{eff} is approximately equal to $Z^{1/4}\ q$, where Z is the atomic number of the fast particle[12], both for the case of the He^+ ions and for the case of the N^+ ions.

A further generalization of the results, both to the case of large Z and to the case of large primary-ion velocities, is of interest.

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